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著者	Ohji Takahisa, Mukhopadhyay S.C., Iwahara Masayoshi, Yamada Sotoshi
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Permanent magnet bearings for horizontal- and vertical-shaft machines: A comparative study

T. Ohji, S. C. Mukhopadhyay,[a] M. Iwahara, and S. Yamada
Faculty of Engineering, Kanazawa University, Kodatsuno 2-40-20, Kanazawa 920, Japan

Two types of magnetic bearing systems employing permanent magnets to be used for vertical-shaft and horizontal-shaft machines, respectively, have been designed and fabricated in our laboratory. In this article we report a comparative evaluation of (i) the permanent magnet configuration and its effect on radial disturbance attenuation, (ii) magnetic losses and their effect on energy storage, and (iii) the off-state position of the rotor magnet in two types of bearing systems. Experimental results are presented. © *1999 American Institute of Physics.* [S0021-8979(99)55708-3]

I. INTRODUCTION

Active magnetic bearing systems, because of their adjustable damping and stiffness characteristics, have many applications in industry worldwide.[1] Permanent magnet bearing systems do not need many electromagnets so they have a simplified control scheme. The structural design, axis of magnetization, calculation of forces, and stiffnesses of different types of permanent magnet bearing arrangements for vertical-shaft machine configuration have been described in Ref. 2. However, many magnetic bearing applications require horizontal operation. Little information regarding the design and control of permanent magnet configurations for horizontal-shaft type magnetic bearing systems has been reported in the literature.

In this article we discuss a few aspects such as the configuration of permanent magnets, radial disturbance attenuation, magnetic losses, and the off-state position of a rotor magnet in two repulsive type magnetic bearing systems that are employed in vertical-shaft and horizontal-shaft machines, respectively.

II. CONFIGURATION OF PERMANENT MAGNETS AND BEARING SYSTEMS

The bearing system developed for the vertical-shaft machine configuration is shown in Fig. 1. The permanent magnet (PM) used for this system is shown in Fig. 2. A circular permanent magnet with either axial or radial magnetization is the only choice for this type of bearing system, making it radially stable. Axially magnetized magnets have been used in the model. The circular permanent magnet used for the vertical-shaft machine, if used for the horizontal configuration, will result in zero levitation force in the central position along the radial (i.e., vertical) direction.[3] So the permanent magnet configuration needs some special attention. Since the radial axis is the noncontrolled passive axis, to reduce the effect of radial disturbance higher radial stiffness is desirable. In order to achieve better radial stiffness, a section of the permanent magnet is placed on the upper section of the stator. Placement of the upper stator permanent magnet will reduce the levitation force, so the arc length should be selected carefully. A finite element analysis was performed to achieve a trade-off between the levitation force and the radial stiffness.[4] The most desirable permanent magnet configuration is shown in Fig. 3 and the magnetic bearing configuration for the horizontal-shaft machine is shown in Fig. 4.

The principal parameters for the vertical-shaft system are the mass of the rotor=5.5 kg, the length of the rotor=420 mm, and the diameter of the rotor=200 mm; those for the horizontal-shaft system are 8 kg, 510 mm, and 220 mm, respectively.

III. RADIAL DISTURBANCE ATTENUATION CHARACTERISTICS

Our aim was to develop a magnetic bearing system with simplified control. Both the systems are unstable along the longitudinal direction. With the help of controlled current electromagnets stability was achieved. The presence of a controller helps to obtain desirable characteristics along this axis. Our interest lies in the noncontrolled raidal axis. To verify whether the system could operate satisfactorily in the presence of a small radial disturbance, the disturbance characteristics were studied by applying a disturbing force along the radial direction. Figure 5 shows the disturbance characteristic along the radial direction for the vertical-shaft machine. It is seen that the system does not loose stability and reaches steady state after some time.

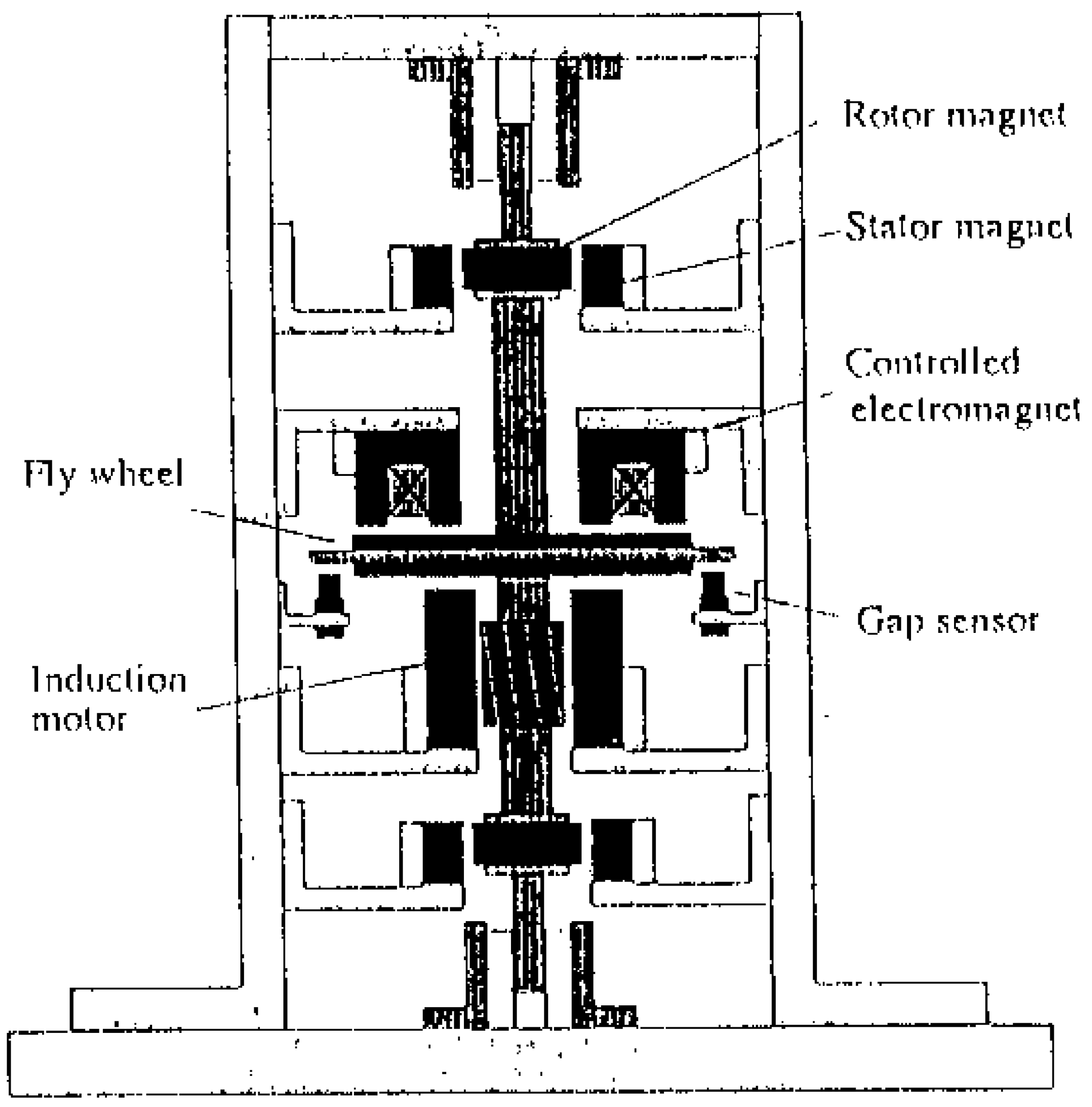

FIG. 1. Configuration of the vertical-shaft machine.

[a]Electronic mail: scmukhopadhyay@hotmail.com

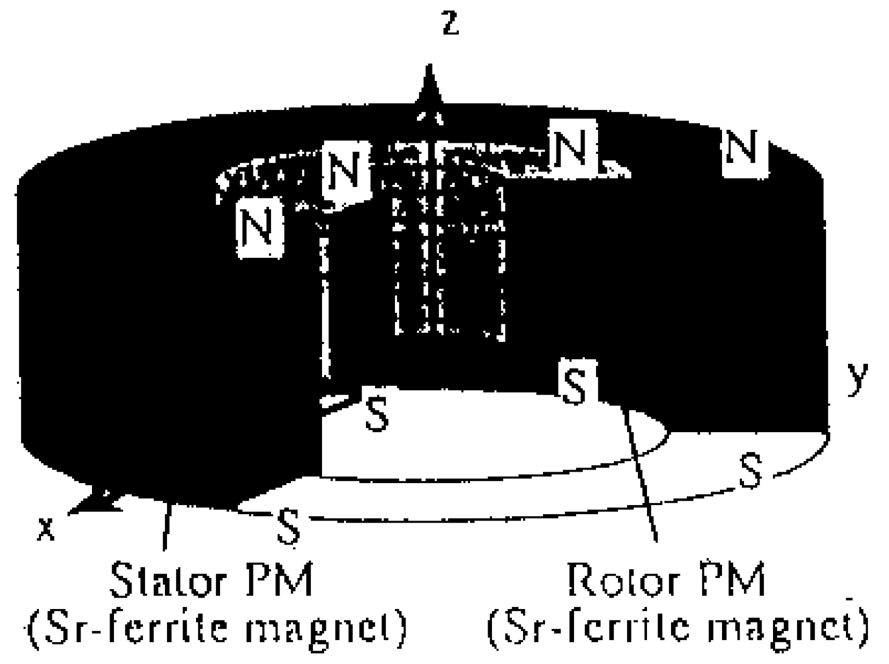

FIG. 2. Permanent magnet configuration (vertical shaft).

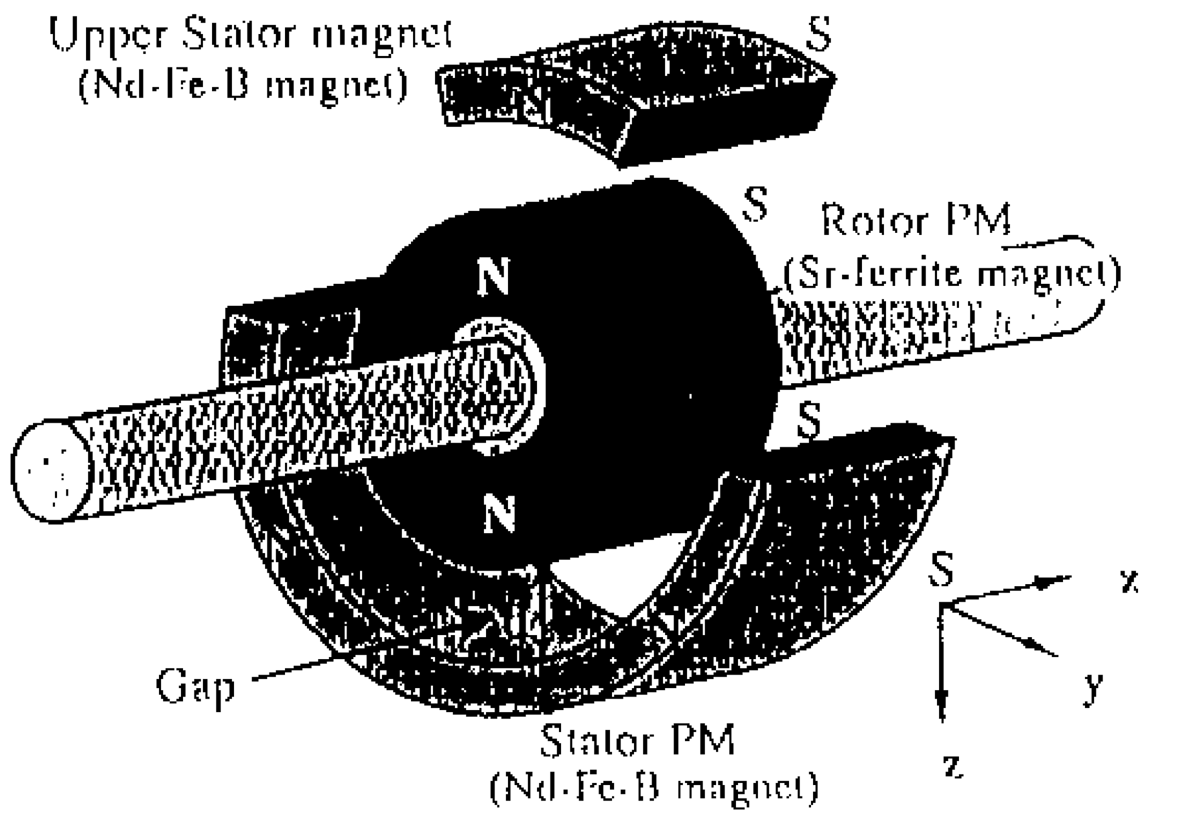

FIG. 3. Permanent magnet configuration (horizontal shaft).

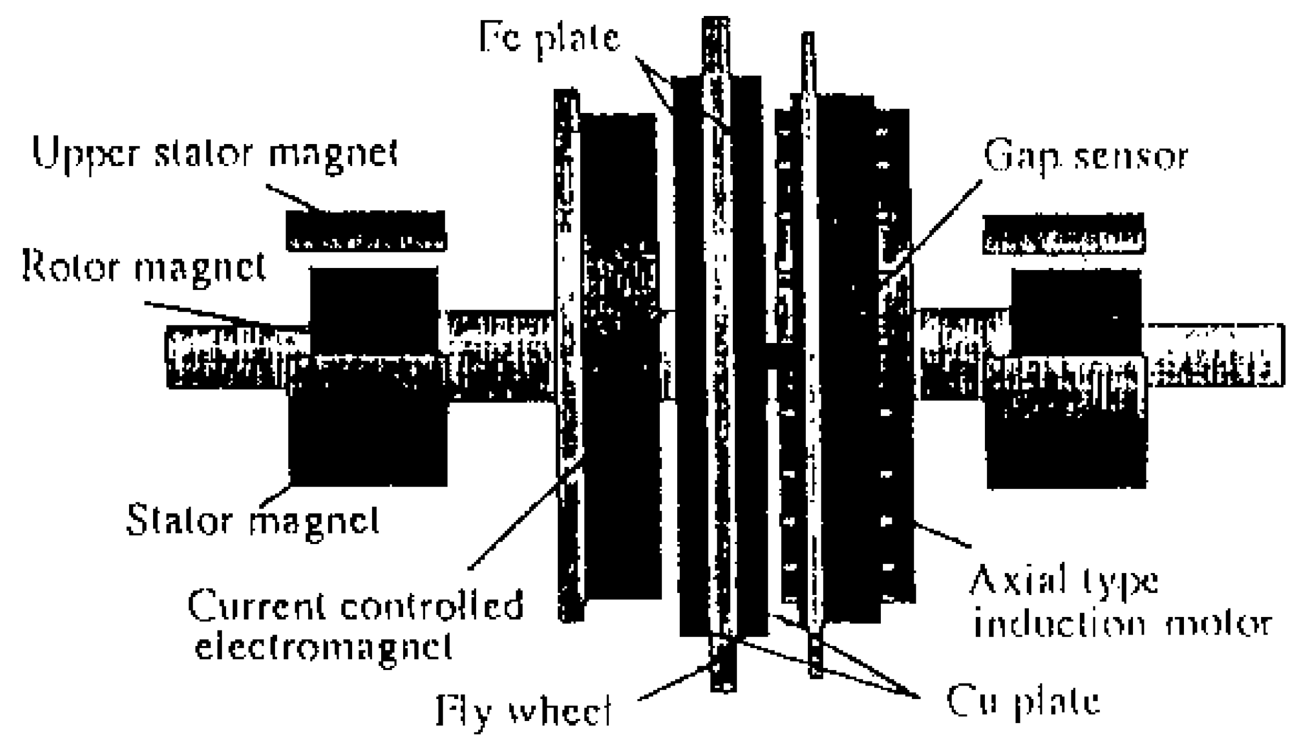

FIG. 4. Configuration of the horizontal-shaft machine.

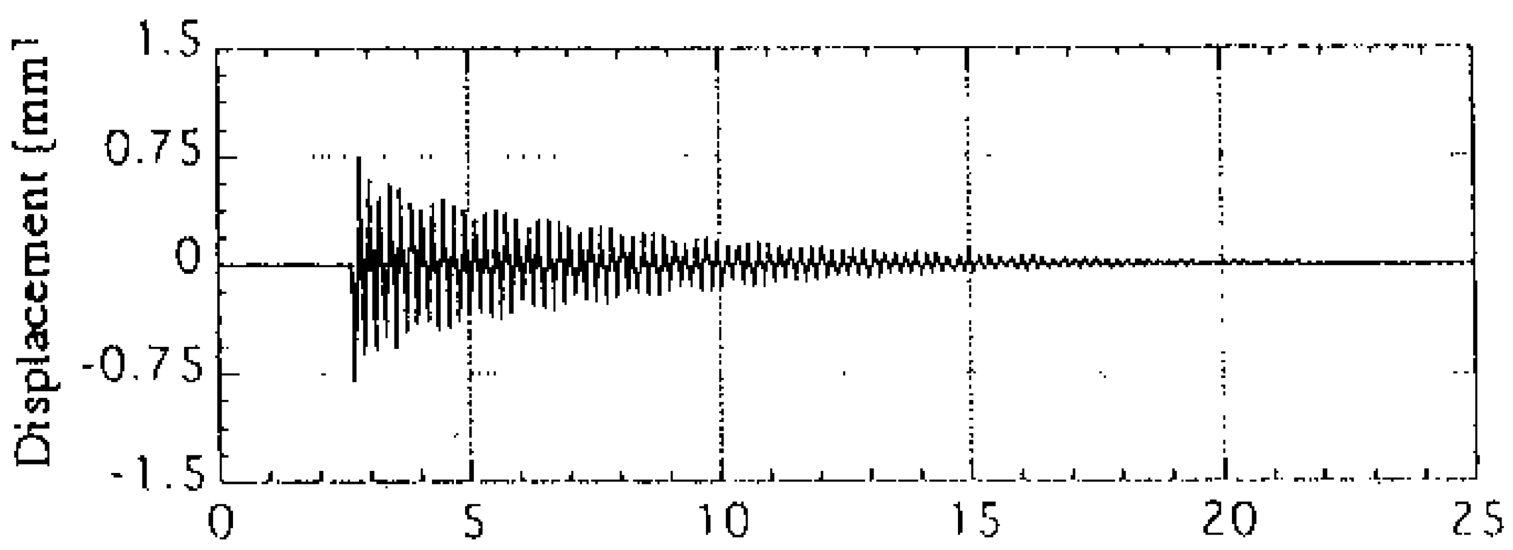

FIG. 5. Disturbance characteristics of the vertical system.

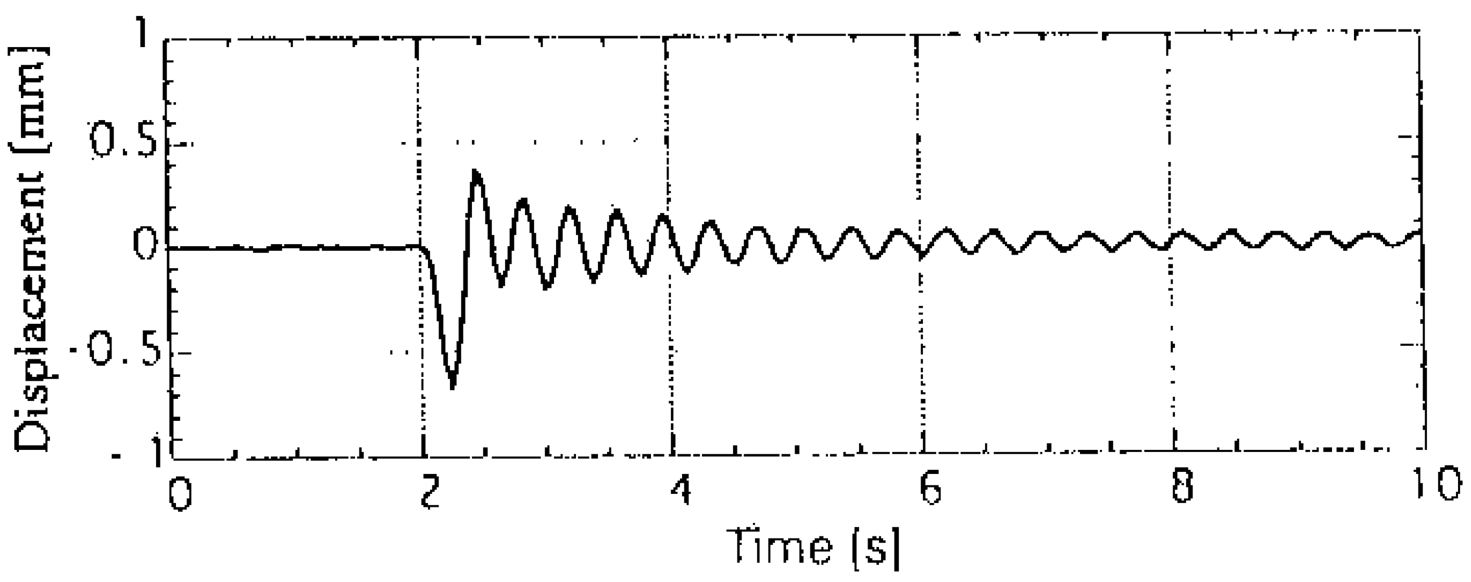

FIG. 6. Disturbance characteristics of the horizontal system without an upper magnet.

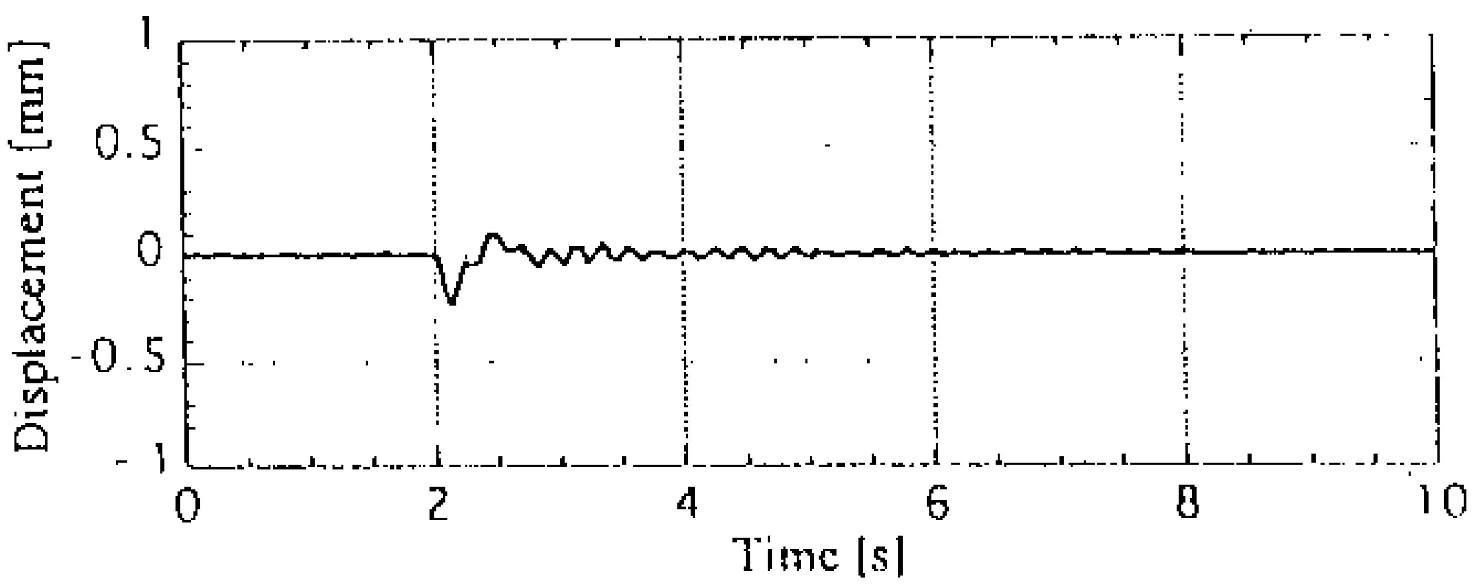

FIG. 7. Disturbance characteristics of the horizontal system with an upper magnet.

The radial disturbance characteristics with and without an upper stator magnet section were studied for the horizontal-shaft machine. Figures 6 and 7 show the disturbance characteristics without and with an upper stator magnet system, respectively, for the same amount of disturbing force along the radial direction. It is seen that the presence of an upper stator magnet has reduced the effect of the disturbance and this is due to the improved radial stiffness characteristics. With the horizontal axis adequately controlled the desired response can be attained.

IV. FIELD DISTRIBUTION AND MAGNETIC LOSSES

The field distribution of the stator and the rotor permanent magnet system of the vertical-shaft and horizontal-shaft systems is not identical due to their different magnet configurations and consequently they have some effect on the magnetic losses. The field distribution has been measured with the help of gauss meter and Figs. 8 and 9 show the flux-density distribution of the vertical-shaft and horizontal-shaft machines, respectively, 1 mm from the stator inner surface. It is seen that the horizontal-shaft machine has a nonuniform flux distribution. Using the above field distribution the magnetic losses are calculated as a function of rotor speed with the help of the finite element method.[4] The loss mainly takes place in the rotor magnet. Figure 10 shows the variation of the magnetic losses with speed for the two types of magnetic bearing systems. For the vertical-shaft machine the magnetic loss is negligible whereas the horizontal-shaft machine has an appreciable amount of magnetic loss.

V. DECELERATION CHARACTERISTICS

If the magnetic bearing is used for the flywheel energy storage system, the deceleration characteristics are very important. In the prototype laboratory models, supply frequency normal induction motors are used so that the speed of operation is not high. Figure 11 shows the deceleration characteristic of the vertical-shaft machine. Since the sizes of the above two bearing systems are not identical, a direct comparison is not possible. But, based on the magnetic loss and total loss, a deceleration characteristic of the horizontal-shaft machine may be drawn and it is also shown in Fig. 11. Due to the presence of magnetic losses in the horizontal-shaft machine, the reduction of speed is faster and consequently the energy utilization will be less.

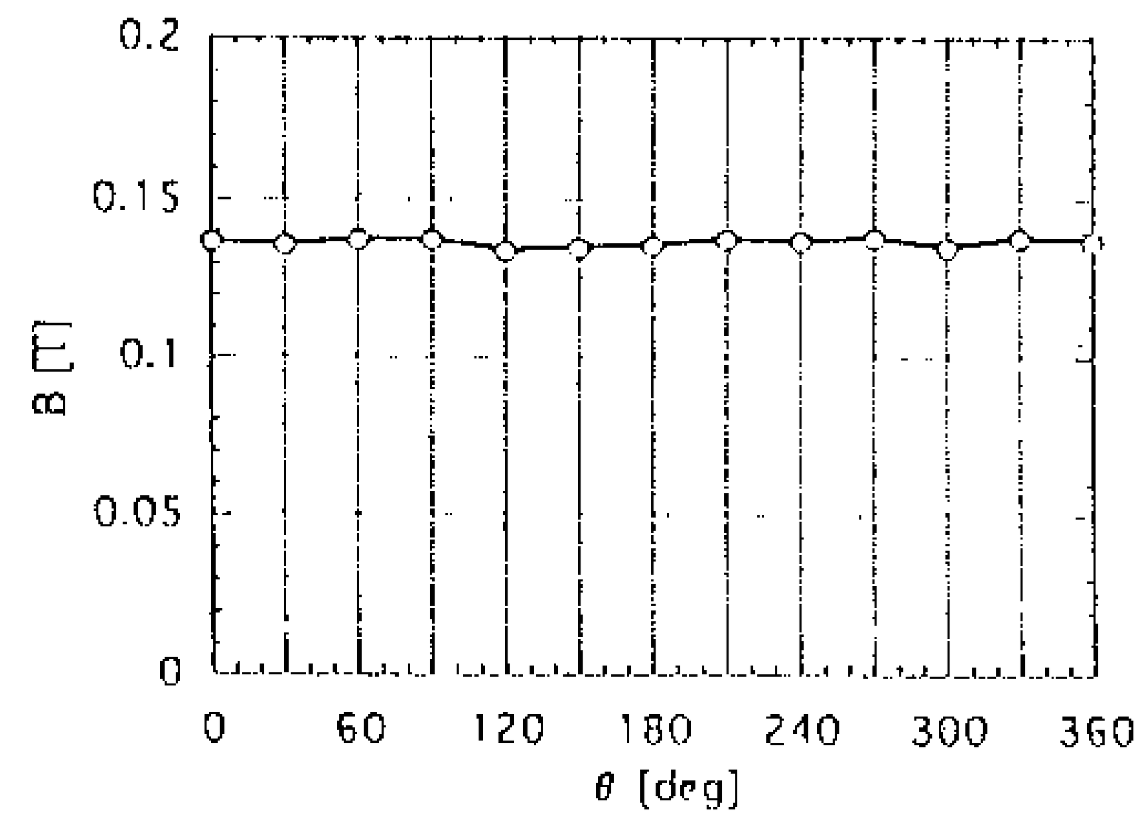

FIG. 8. $B-\theta$ diagram for the vertical system.

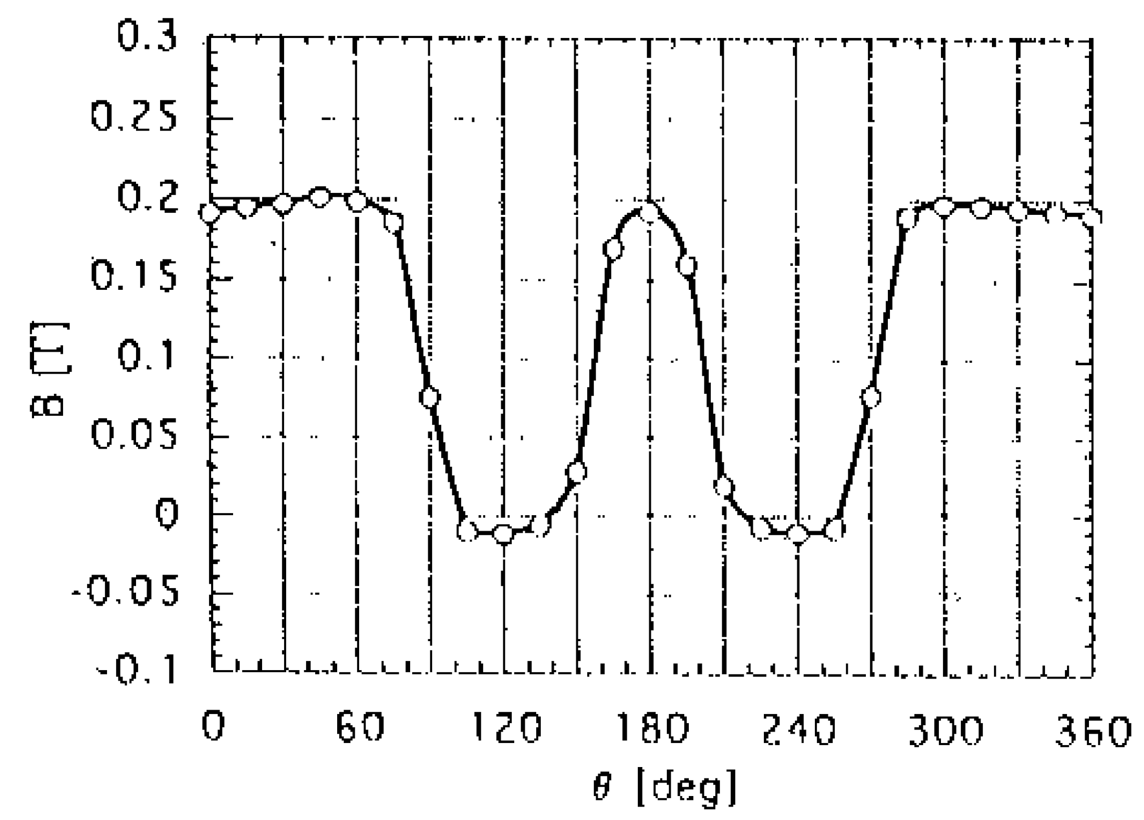

FIG. 9. $B-\theta$ diagram for the horizontal system.

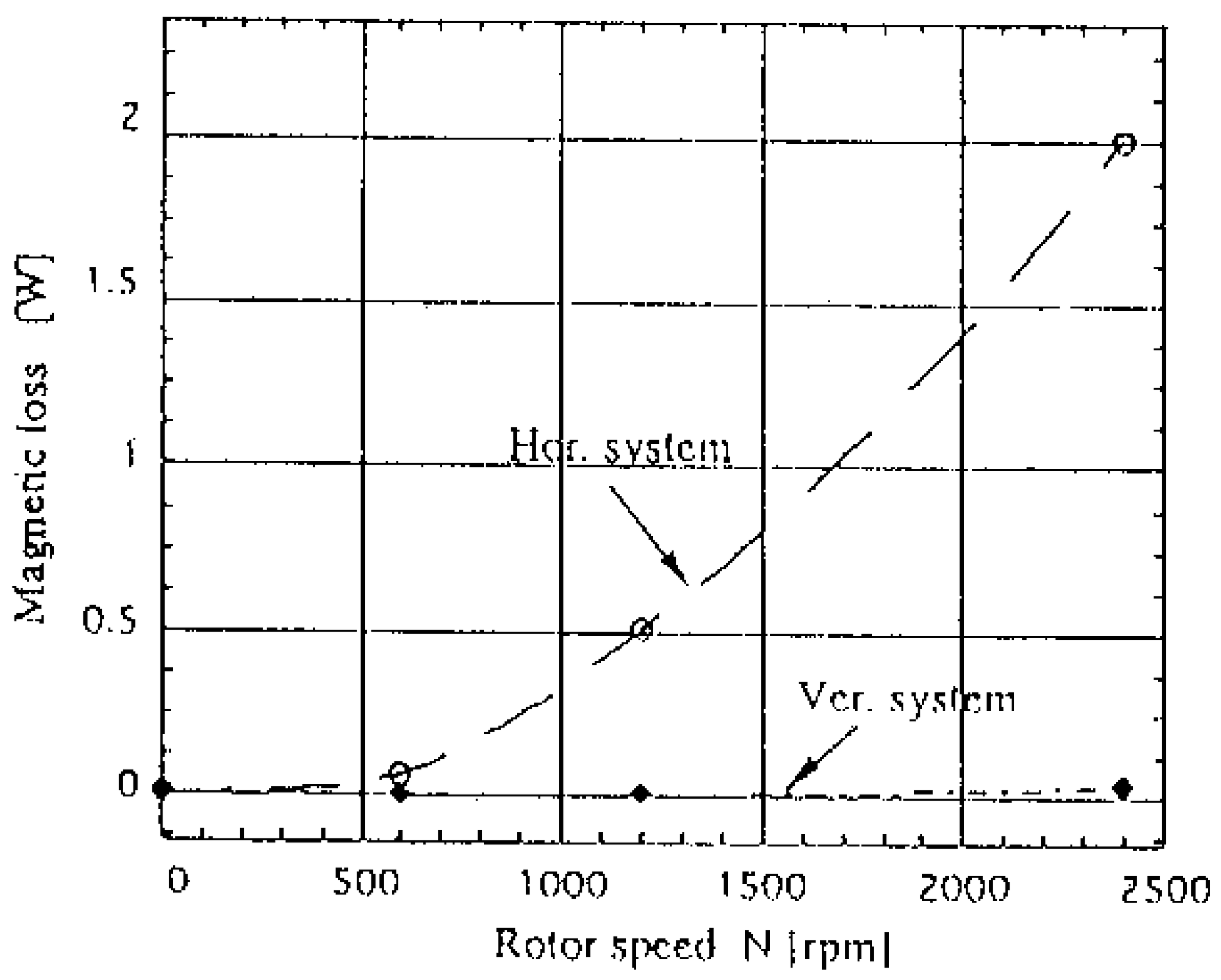

FIG. 10. Loss curves for vertical and horizontal systems.

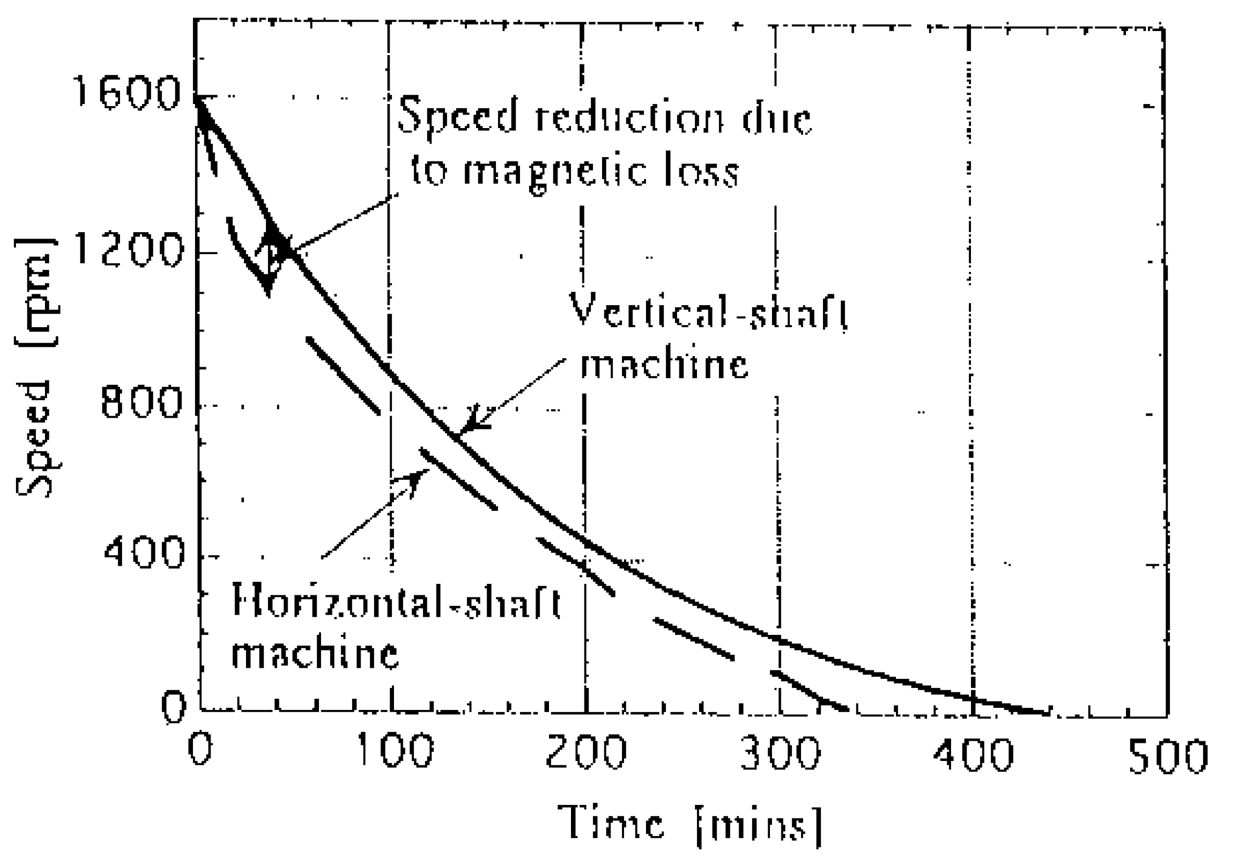

FIG. 11. Deceleration characteristics.

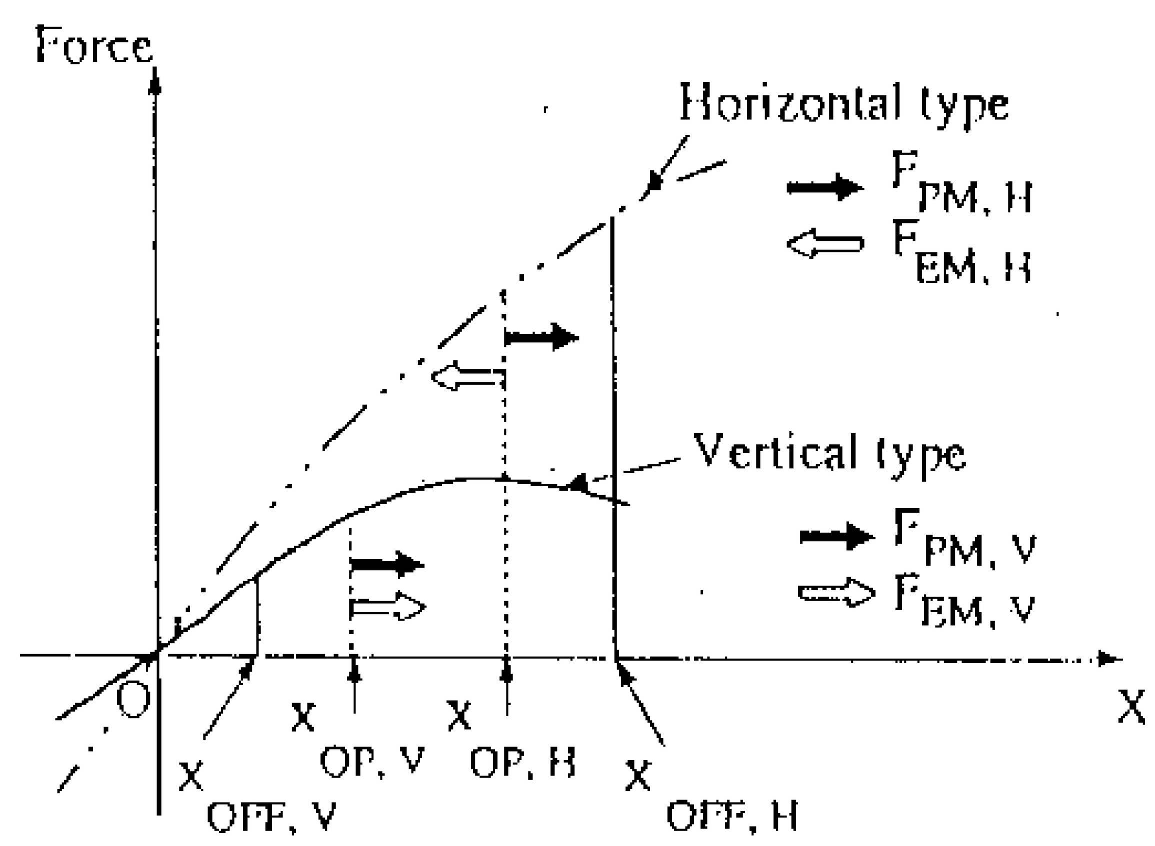

FIG. 12. Off-state rotor position.

VI. OFF-STATE POSITION OF THE ROTOR PM

Due to the unstable nature of the system along the longitudinal direction, the rotor goes to the extreme of either ofthe two sides and is stopped by the stopper plate. In the vertical-shaft machine the force generated by the electromagnet not only maintains the rotor in the desired position but it also constitutes part of the levitation force. Both the repulsive forces due to permanent magnets and the attractive force due to the electromagnet act in the same direction and, when they join together at a particular position, the rotor is able to levitate. The repulsive forces due to two sets of stator–rotor permanent magnets at two sides are unable to levitate the rotor. In the off state the rotor goes down to X_V as shown in Fig. 12, i.e., on the left of X_{OP}, the operating point. In the horizontal-shaft machine the electromagnet has only one function, i.e., to maintain the rotor in a stable position. The force generated by the electromagnet acts in the direction opposite that of the permanent magnet. In the off-state position the rotor is dragged by the repulsive force and goes to X_H, i.e., on the right of X_{OP}.

VII. CONCLUSIONS

In this article we have studied different aspects such as the permanent magnet configuration, disturbance attenuation, field distribution, magnetic losses, deceleration characteristics, and off-state position of the rotor of two types of magnetic bearing systems that are employed for vertical-shaft and horizontal-shaft machines. Although the type of magnetic bearing system used depends on the machine configuration, the specific application requirement, and other criteria, this study can provide first hand knowledge of a few aspects of two different types of repulsive type magnetic bearing systems for the designer.

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